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AIRIS Wide Area Detector for Integrated Early Warning

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ABSTRACT

We discuss the development of the AIRIS technology for the standoff detection, identification, and tracking of chemical warfare agents (CWA), toxic industrial chemicals (TIC), and biological warfare agent aerosols. This sensor is capable of detecting CWA vapors at levels required of the non-imaging JSLSCAD sensor, as well as many TICs, at their toxicity threshold. The development of this sensor will meet the need to detect smaller scale chemical releases at ranges to 5 km and in urban environments. The sensor will also provide the capability to perform on the move detection by providing data acquisition at 5 data cubes/second.

1. INTRODUCTION

Under funding from the US Army Edgewood Chemical and Biological Center and the Defense Threat Reduction Agency, Physical Sciences Inc. (PSI) is developing its Adaptive Infrared Imaging Spectroradiometer technology (AIRIS) as a candidate for the Joint Service Wide Area Detector and related standoff chemical warfare agent (CWA), toxic industrial chemical (TIC), and biological warfare agent aerosol detection, identification, and tracking applications. The AIRIS Wide Area Detector (AIRIS-WAD) is a direct imaging passive multispectral sensor that has been successfully demonstrated in the breadboard stage in the laboratory as well as in field tests, in both ground and airborne configurations. This sensor is capable of detecting CWA vapors at levels required of the non-imaging JSLSCAD sensor, as well as many TICs, at their toxicity threshold, as identified by the U.S. Army Center for Health Promotion and Preventive Medicine. The breadboard system has now been developed into a fully integrated prototype that will resolve several outstanding problems in remote CB detection, most significantly, the need to detect smaller scale chemical releases at ranges to 5 km and in urban environments. The AIRIS-WAD sensor provides the capability to perform on the move detection in three ways: 1) by providing data acquisition over a 32 x 32 degree field of view with real-time processing at 5 data cubes/second, scanned over a 360 degree azimuth x 60 degree elevation field of regard, 2) by packaging the sensor so that it can be qualified for deployment on Predator or Firescout class UAVs in addition to UH-1/60 rotorcraft, C-130 aircraft, as well as Fox/Stryker reconnaissance vehicles; and 3) by implementing algorithms that use the minimum number of wavelengths required for detection, thereby enabling a greater rate of spatial coverage for the same data rate.

The AIRIS-WAD sensor uses passive infrared measurements to detect and track CWAs, TICs, and BWAs. Passive infrared remote sensing of toxic releases requires exploitation of both the spectral signatures of the target species as well as a thermal contrast between the air parcel containing the chemical release and the background scene. The basic AIRIS technology comprises an LWIR focal plane array-based camera which views the far field through a low-order, tunable Fabry-Perot etalon. The

tunable etalon provides the spectral resolution necessary to resolve structured absorption and emission from molecular vapors and aerosols. The focal plane array (FPA) enables radiance measurements of sufficient accuracy that chemical vapors and aerosols may be selectively detected with only several degrees effective temperature difference between the vapor and the background. In breadboard form, the AIRIS technology has been successfully demonstrated in a range of field measurements dating to 1998.

2. SYSTEM OVERVIEW

The AIRIS-WAD prototype is a fieldable sensor system having a 32 x 32 degree FOV direct imaging "Camera Mode" and a 360 x 60 degree field of regard (FOR) "Scanning Mode" when equipped with a rotary turntable. The high spatial resolution of the system is achieved by utilizing a 256 x 256 element HgCdTe FPA subtending the 32 x 32 degree FOV to provide a diffraction-limited 2 milliradian IFOV per pixel. The prototype has been designed to meet MIL-810-F for thermal, shock, vibration, and weather and MIL-461/462 for EMI. The system comprises a Sensor Unit (SU), Operator Display Unit (ODU), and Power Unit (PU). The 360 x 60 degree FOR is achieved by positioning the SU FOV in 24 orientations around the compass over a 90 second interval using a rotary turntable. System design goals are 50 lbs and 250 Watts for the combined SU/ODU. The PU will operate using 120VAC line current or 20-32VDC power. The AIRIS-WAD prototype system will have the following capabilities:

- Provide passive detection and tracking of CB releases at ranges to 5 km with 10 meter spatial resolution.
- Provide detection of nerve (VX, GA, GB, GD, GF at 135 mg/m2) and blister (HD, HN3, L at 3,300 mg/m^2) agents in desert, urban and spatially cluttered environments with detection probabilities exceeding 0.9 and false alarm probabilities less than 10^{-4}, both per measurement.
- Incorporate detection of TICs at the level defined as severe in USACHPPMs Toxic Industrial Chemicals Info Card.
- Incorporate detection of compounds associated with the production of CB agents to provide intelligence on production activities and post strike damage assessment.
- Provide RADAR-style plots and direct image display of the environment with JWARN interface.
- Provide real-time acquisition and processing of 32^o x 32^o CB images at 5 images/second and 360^o azimuth x 60^o elevation coverage in 90 seconds.
- Enable Stryker/Fox vehicle integration and provide a roadmap for UH-1/60, C-130/UAV deployment.
- Design and construct to sensor system prototypes to meet MIL-STD-810F for shock, vibration, drop, immersion, and temperature and MIL-STD-461/462 for EMI.

PSI has developed a draft operational requirements document (ORD) for AIRIS-WAD that closely follows the Commercial JSLSCAD ORD. However, this document includes capabilities inherent in the AIRIS-WAD system and reflects the need for higher spatial resolution and higher data acquisition speeds to perform "on the move" detection.

3. SENSOR UNIT

The housing design for the Sensor Unit is shown in **Figure 1**. A photograph of the integrated FPA and tunable filter system is shown in **Figure 2.** The basic sensor concept, as well as many of its applications, was developed by PSI and they are described in prior publications.[1-7] The sensor unit comprises a 256 x 256 element HgCdTe FPA and its drive electronics, the AIRIS tunable filter and its drive electronics, a 5 element expansion telescope to provide a diffraction limited image over a 32 x 32 degree field of view, an FPGA/DSP based image processor unit, a system controller, and a combined blackbody calibrator/prism actuator. Each of the sub-systems will be described later in this paper. The total system weight of the optical components and control/data processing electronics is approximately 57 lbs. During steady state operation approximately 150 watts of power is dissipated within the sensor unit, of which about 70 watts is from the detector cryocooler and the remainder from the electronics. The sensor unit is air-cooled and uses a series of heat pipes to pass heat to the rear of the chassis, where a high efficiency heat sink/fan combination is used to maintain all system components within allowed operating temperature limits under environmental temperatures up to 49 degrees C.

Figure 1. Designs of the Sensor Unit on its rotation stage.

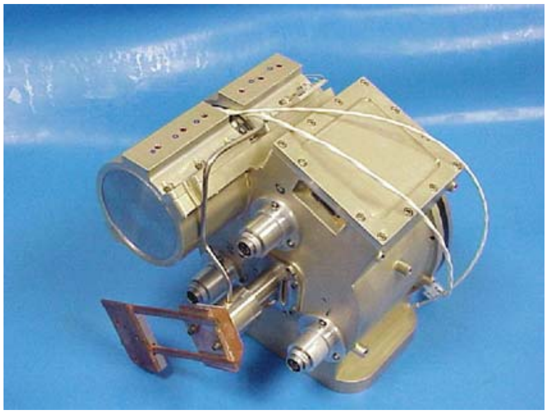

Figure 2. Photograph of sensor module.

The system's 256 x 256 element HgCdTe FPA was specially developed for the AIRIS-WAD sensor by BAE Systems (Lexington, MA), with custom readout electronics made by Vtech Technologies (Andover, MA). The array has optimized spectral response from 8 to 11.2 µm and sensitivity matched to the spectral throughput properties of the AIRIS tunable filter (nominal 60% peak transmission and 10 cm^{-1} spectral bandwidth). A custom bandpass filter on the detector cold shield limits the infrared radiation reaching the detector to a single order of interference from the interferometer. A specially designed 19 mm focal length f/1.2 lens system, integral to the cold shield, provides a collimated field of view for the detector array looking through the closely-coupled Fabry-Perot tunable filter, which is operated at ambient temperature. An integral Stirling-Cycle cryocooler maintains the FPA, cold shield and filter, as well as the lens assembly, at approximately 65K to reduce overall system noise to about 1 uW/(cm^2 sr^{-1} μm^{-1}).

The AIRIS tunable filter module (TFM) utilizes three Burleigh inchworm motors to drive one moving mirror with respect to a fixed mirror. A capacitance micrometry system is used in conjunction with a closed loop control system to position and align the mirrors to transmit a specific wavelength of light to the FPA. Several major improvements have been made to this design over the prior breadboard units. New inchworm drive control electronics have been developed to replace the commercial unit supplied by Burleigh. The new electronics provide the ability to move the actuators on the order of a few microseconds using solid-state power supplies. The mounting arrangement for the mirrors was changed to a flexure system to provide greater lateral stability under high vibration loads as well as greater passive alignment stability. The capacitance micrometry system was improved to provide temperature compensation for improved calibration stability as well as faster readout rates. Finally, the entire control system was moved from a PC-based platform to a dedicated FPGA. The overall impact of these performance improvements was a reduction in wavelength tuning time from 15 ms to approximately 1.5 ms while achieving a calibration accuracy of 0.5 cm^{-1}. The interferometer is operated in a

combination of second and third order to optimize spectral tuning and resolution. **Figure 3** shows a photograph of the TFM controller while **Figure 4** shows a typical transmission curve for the interferometer.

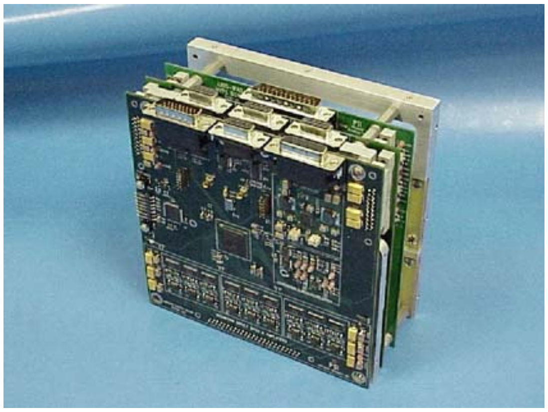

Figure 3. Photograph of TFM assembly.

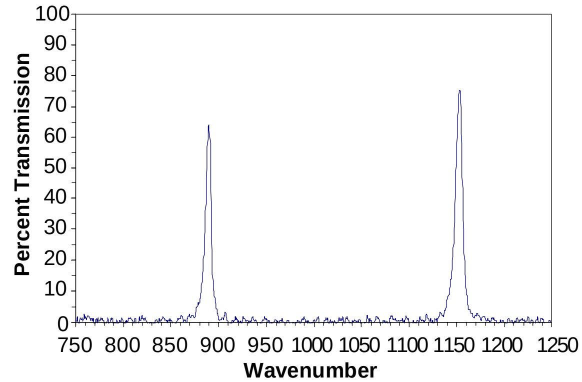

Figure 4. TFM transmission spectrum showing nominal 10 cm^{-1} spectral bandwidth and 60% peak transmission.

Radiometric calibration of the system is provided using an on-board, two temperature blackbody assembly. The assembly comprises two thermoelectrically temperature stabilized blackbody plates located on a precision slider mechanism. The temperatures of the blackbodies are set such that one is approximately 15^{o} C above ambient temperature and the other is approximately 15^{o}C below ambient temperature. Either blackbody can be positioned to fill the field of view of the sensor. At start up, and subsequently periodically during operation, the on-board system controller automatically commands the acquisition of calibration data that is used to apply an individual gain and offset correction for each pixel in the array at each wavelength utilized in the detection algorithm. A second slider mechanism in the blackbody assembly hold a pair of infrared prisms which can be inserted into the filed of view of the sensor unit. In Scan Mode these prisms deflect the 32 x 32 degree field of regard of the FPA vertically to provide nominal -15 to + 15 degree and +15 to +45 degree fields of regard with respect to the horizon.

The algorithm employed in the AIRIS-WAD system is based on the use of Gram-Schmidt ortho-normalized Principal Component basis functions, which are combined with an Orthogonal Sub-space Projection Operator approach to estimate and remove the background spectrum of the scene from the multispectral data. A Spectral Angle mapping approach, in which the correlation between each background-nulled pixel spectrum and the target reference spectrum is determined, is used to test for the presence of a specified target compound. Pixels where both the Spectral Angle correlation and differential radiance relative to the background exceed pre-determined threshold values are identified as corresponding to the target compound. Detection thresholding on the basis of both spectral similarity and intensity reduces the probability of false alarm without significantly degrading the probability of target detection. This algorithm is implemented in a combined FPGA/DSP image processor, jointly developed by PSI and Vtech Technologies, and integrally coupled to the FPA detector to permit high speed detection of the CWAs and their simulants. The processor, shown in **Figure 5**, comprises a XC2V6000-6BF957C (Virtex II) series FPGA and an ADSP-TS101SAB1-100 DSP (300 MHz TigerSHARC) from Analog Devices. The processor can radiometrically calibrate and execute the detection algorithm on a 20 wavelength 256 x 256 pixel data cube at rates exceeding 5 cubes per second. Reduced wavelength data cubes (5 wavelengths) can be processed at near video rates. The DPG/PNNL infrared spectral libraries are used for the detection of CWAs as well as TICs.

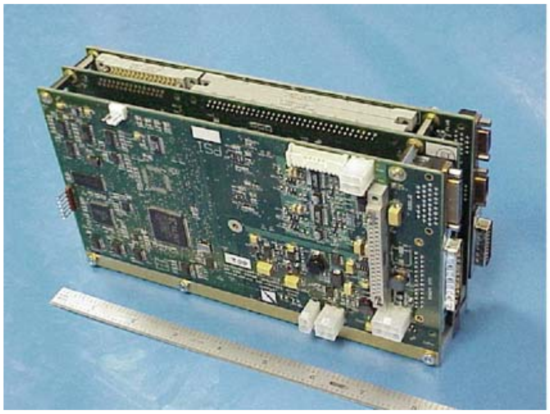

Figure 5. System controller and image processing board assembly.

4. OPERATOR DISPLAY UNIT

The system ODU is shown in **Figure 6**. The ODU is based on a MIL-810/461/462-qualified display from L-3 Communications. This unit has dimensions 12” x 10” x 4” and weighs 8 lbs. It can be mounted in a console for various platform integrations or can be used with a mounting stand for stand alone operation. It interfaces to the Sensor Unit through the system controller, which is integral to the Sensor Unit. The ODU uses a menu interface to control system operation through a series of buttons on the front panel. A window on the display shows system status, detection history, any error messages, and communications status. Two display modes are enabled on the ODU: Camera and Scan modes. In the Camera Mode the field of regard of the sensor is positioned by the platform on which it is mounted or by the on-board rotary table. Individual data cubes are acquired, analyzed for the presence of threat chemicals, and the color coded results of that analysis overlaid on a thermal infrared image of the scene acquired with the sensor. A simulation of this mode is shown in **Figure 6**.

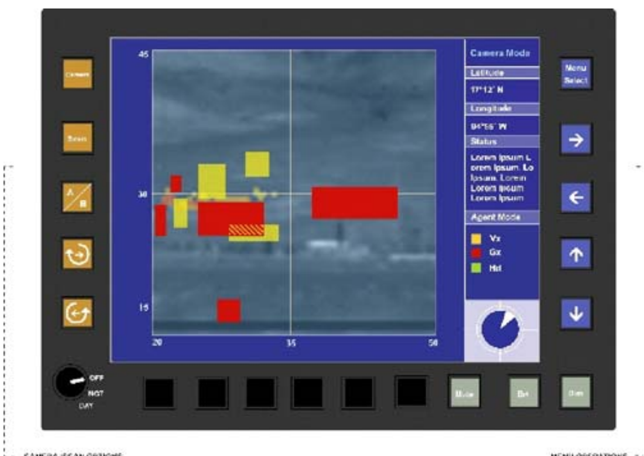

Figure 6. Design for ODU display in Camera Mode as implemented on the L-3 Communications display module.

In Scan Mode the system controller commands a rotary turntable to position the sensor unit to each of 12 positions around a 360 degree circle and acquire data at each position. At each compass position the prism deflector directs the sensor field of regard to acquire data cubes at orientations of -10 to +20 degrees and +20 to +50 degree fields of regard with respect to the horizon, such that 24 data cubes covering a 360 azimuthal x 60 degree elevation extent have been obtained. The results of the analysis of the individual data cubes are stitched together by the system control software and displayed on a RADAR style plot to provide situational awareness. A digital compass on-board the Sensor Unit provide absolute directional reference and the Sensor Unit is capable of received NMEA 0183 GPS messages to provide absolute positional reference to anchor the RADAR plot display. The RADAR plot can be overlaid on a digital terrain map stored in memory to provide additional situational awareness to the user, as shown in **Figure 7**.

Additional spatial filtering approaches are used to reduce uncorrelated single pixel and correlated edge-induced false alarms. Images are reduced to a binary format in which detection pixels have a value of unity and non-detection pixels have a value of zero. A two-step dilation and erosion algorithm is first conducted. The dilation operation determines if each pixel has any neighbor that is non zero. If it has, that pixel also is made non-zero. If not, it remains the same. The dilation operation will fill in gaps in the structure of the chemical cloud due to local turbulence or locally poor thermal contrast, smooth borders, and slightly enlarge the size of the cloud. The erosion process does the opposite of dilation. If any neighbor pixel is zero, the pixel is set to zero. This process reduces the image object to its original size. This sequence will result in smoothed regions of non-zero pixels representing detection clouds. It also

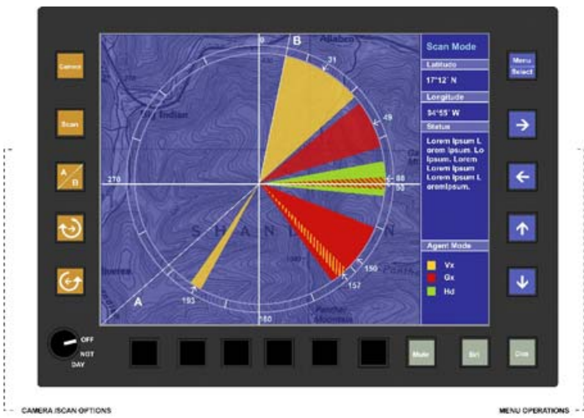

Figure 7. Design for ODU display in Scan Mode as implemented on the L-3 Communications display module.

suppresses single pixel false alarms. A perimeter function is then applied. The perimeter function keeps all perimeter pixels non-zero, setting all interior pixels to zero. This function defines cloud edges for boundary determination and also suppresses false alarms at edges, where they are typically one pixel wide. Finally, a boundary function is applied that lists the X/Y components of the remaining perimeter pixels. These coordinates are converted into azimuth and elevation boundaries using data from the on-board digital compass and provide the cloud location data for transmission via JWARN and display on the ODU. We note that without the high spatial resolution inherent in the AIRIS-WAD system such operations, and the concurrent reduction in false alarm rate, would not be possible.

CONCLUSIONS

The AIRIS-WAD sensor is currently completing its test and integration phase. Key elements of the system have already met their performance goals. Two additional units are currently being produced for evaluation under the DT-JSLSCAD trials to be conducted in 2005. In addition to the DT-JSLSCAD trials in 2005, an AIRIS-WAD sensor prototype will be installed in a GPS-directed POD on a UH-1 helicopter and flown in pseudo-UAV mode in which detection data will be telemetered to a ground station. Additional tests are planned to probe the detection of biological aerosols and toxic industrial chemicals.

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